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A Study of the Impact of Individual Thermal Control on User Comfort in the Workplace: Norwegian Cellular vs. British Open Plan Offices

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Abstract

In modern offices, user control is being replaced by centrally operated thermal systems, and in Scandinavia, personal offices by open plan layouts. This study examined the impact of user control on thermal comfort and satisfaction. It compared a workplace, which was designed entirely based on individual control over the thermal environment, to an environment that limited thermal control was provided as a secondary option for fine-tuning: Norwegian cellular and British open plan offices, respectively. The Norwegian approach provided each user with control over a window, door, blinds, heating and cooling as the main thermal control system. In contrast, the British practice provided a uniform thermal environment with limited openable windows and blinds to refine the thermal environment for occupants seated around the perimeter of the building. Field studies of thermal comfort were applied to measure users' perception of thermal environment, empirical building performance and thermal control. The results showed a 30% higher satisfaction and 18% higher comfort level in the Norwegian offices compared to the British practices. However, the energy consumption of the Norwegian case studies was much higher compared to the British ones. A balance is required between energy efficiency and user thermal comfort in the workplace.

Keywords: Thermal comfort, energy, individual control, personal office, open plan workplace

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1. Introduction

There is a gap between literature and practice in the field of thermal comfort, as literature suggests the use of thermal control for occupants to increase their satisfaction and comfort. In contrast, in practice centrally operated thermal systems are applied and occupant control of the thermal environment is avoided. Currently in the field, thermal comfort and control are mainly researched regarding the engineering aspect of the indoor thermal environment examining what temperatures satisfy all occupants. Accordingly, engineering solutions are examined to be added to the building to improve the thermal comfort of occupants. This study investigates thermal comfort from an architectural point of view and the impact of architectural design, different paths in the history of workplace design and their impact on occupants' thermal comfort and satisfaction.

The history of workplace design shows the continuous demand of users to control their thermal environment [1]. However, climate change, technological advances, economic challenges, new ways of working, organisational changes and goals have driven the design away from the immediate demands of users. Organisational goals are currently replacing workers' rights, including those pertaining to thermal control [2]. Recently, the Workers' Council is losing its impact to protect the demands of users in Europe [2]. In this context, cellular plan offices no longer respond to organisational changes and challenges in the twenty-first century, due to their high cost and lack of flexibility [2,3]. As a consequence, open plan offices with limited environmental control are replacing personal offices with high levels of individual thermal control in Scandinavia [4,5]. In the open plan workplace, users' control over the thermal environment is being replaced by automated thermal systems in order to simplify regulating the thermal environment and to avoid individuals tampering with the system [6,7]. There is a disagreement between researchers as whether thermal control is necessary for the workplace in the future. Some researchers predict it as unnecessary, as flexible ways of working replace assigned workstations [8]. However, to attract a talented workforce and to maintain performance, organisations will have to provide work environments that meet the demands of users [9], and occupants prefer access to thermal control in order to feel comfortable [10-12], thus user orientated design of thermal control systems will be essential [9].

This study investigated the impact of providing high levels of individual control over the thermal environment on user satisfaction and comfort in the workplace. Comparing the two distinct approaches (Norwegian and British) in providing thermal control in the workplace is the significance of this study. The control systems in Norwegian personal offices, which are getting less common, were compared to that in British open plan offices

with limited thermal control, which are becoming common practice even in Scandinavia. This was related to the architectural design of the building, history, regulations and the contexts of the two countries, which lead to different ways of providing thermal control for occupants. The influence of architectural design on comfort and decision making of occupants in using the available thermal control was investigated. Four buildings were compared, two Norwegian personal offices (buildings a and b) and two British open plan offices (buildings c and d). Building a was built in year 2000, building b and c in 2006, and building d in 2011. Building a received a c rating and building b a b rating for energy consumption. Building c received an excellent BREEAM rating (84%), the highest Environmental Performance Indicator (EPI) rating (10 out of 10), and won an award from the British Council for Offices. Building d received a very good BREEAM rating, a b score for energy consumption and an award from British Council for Offices.

2. Architectural Design of the Workplace

After 1960s, Northern European and Anglo-Saxon countries followed two separate paths in designing the workplace layout: user-oriented and business-oriented, respectively. The significant difference is highlighted in ‘the quality of the working environment between the Anglo-Saxon developer-based offices and custom-built Northern European offices’ [10]. The ‘Social Democratic Office’ [11] resisted the North American managerial and mass production concepts [12,13,1]. Albeit employees demanded the same rights in both places, in 1970s the Workers’ Council in Scandinavia succeeded to protect workers’ rights, including access to thermal control, natural light and ventilation [1]. Thus Scandinavian offices were designed according to users’ demands and workers’ rights. The traditional cellular plan office layout was reintroduced with much higher standards [14]. The employment culture was based on providing pleasant environments rather than higher wages [11,15]. Hence individual control over the thermal environment was provided in a personal office for each occupant. ‘The most radical reaction took place in Sweden, where it became common practice to give every employee a private office with individual climate control, daylight and an outside view’ [1]. The Scandinavian cellular plan offices were criticised for not being suited for organisational changes and challenges in the 21st century, due to being expensive and inflexible [2,11].

On the contrary, the British organisations followed Northern American managerial system, Fordism [11-13,16] and office design [1]. After the 1970s in the UK, open plan offices were designed [1,17], as they supported modern technological advances [18], flexible communication [19], organisational changes [10,20-22], and work

and economic efficiency [23,24]. The earlier inventions of air conditioning in 1930s and florescent lights in 1940s led to deeper open plan layouts. They reduced the requirement for natural light and ventilation and offered higher occupancy and efficiency in the use of space [17]. Standard criteria were introduced to regulate the indoor thermal environment of the workplace [25]. Although organisations gained from the open plan layout, employees did not benefit much from it [1], due to distractions [26-32] and lack of individual environmental control [10]. The open plan layout is 'more generic and less responsive to individual control' [22]. It reduces user satisfaction, engagement and motivation to work [31,33,34], perceived privacy [26,35,36], and it increases physical stress [34]. Although business-oriented and user-oriented approaches led to separate workplace designs, some organisational and individual criteria are beneficial for both parties. For instance, user satisfaction and health are related to higher productivity [37] and less absenteeism [38,39], respectively.

Norwegian workplace regulations are more precise and comprehensive compared to the British legislations, which are less clear and they are open to interpretation. In Norway, the use of openable windows, natural ventilation, user friendly blinds, and individual temperature control are required for every individual in the workplace. Effective ventilation with a clean and fresh outdoor air supply are required, with a ventilation rate between seven to ten litres per second per person [40]. On the contrary, the British regulations are more vague in explaining that sufficient light, ventilation and a comfortable temperature are required. Although natural light is recommended, it is not obligatory: 'as is reasonably practicable' [41]. Overall, individual environmental control is highly valued in the Norwegian regulations, while it is hardly mentioned in the British legislations.

Higher thermal control is associated with higher user comfort and satisfaction [6,42-49]. However, there is a difference in providing thermal control in the Norwegian cellular and British open plan offices. The latter is based on supplying a uniform and standard thermal environment [25]. The main thermal system is centrally operated to ensure the indoor air quality, particularly when occupants prefer not to open the windows. User control is provided as a secondary option only for 'fine-tuning' in case of a system failure [50] or in case occupants were uncomfortable [6]. In contrast, in Scandinavia, individual differences and perceptions of thermal environment are highly respected. Thus, individual thermal control is the main source of adjusting the thermal environment although a central system operates in the background to ensure the indoor air quality. Every individual is provided with thermal control and they are expected to adjust the thermal environment of their personal office according to their requirements.

This study compared user comfort and satisfaction in Norwegian and British workplace contexts, as user satisfaction is related to higher levels of productivity [37], which is beneficial for both individuals and organisations. The case study buildings were selected from recently constructed buildings (less than ten years old) and their performance was evaluated to limit the impact of the quality of the indoor thermal environment on users' view. Interviews clarified the impact of contextual factors on thermal comfort. The occupants' comfort and satisfaction were recorded and compared between the two case studies and users' view of thermal control was investigated through follow up interviews.

3. Methodology

The study compared users' comfort and satisfaction as well as the energy consumption of two workplace settings with high and low environmental control systems. Buildings A and B were the Norwegian practices with high levels of thermal control and Buildings C and D were the British practices with low levels of thermal control. The relationship between users' view and thermal performance of the building were further investigated. Field studies of thermal comfort were applied with a particular emphasis on grounded theory. Occupants' perception of the thermal environment was recorded using survey questionnaires, building performance was evaluated through environmental measurements and thermal control was further investigated through semi-structured interviews. User comfort and satisfaction were compared in two cellular plan offices in Norway and two open plan offices in Scotland in summer 2012 and the duration of the study in each building was one week. The fieldwork was undertaken during the summertime, as overheating in this season is becoming a major problem in the workplace in European countries [51,52]. In order to limit the impact of different climatic conditions on user's view, summer was selected for the fieldwork as the outdoor climatic conditions of Norway and Scotland are relatively similar. The air temperature in Oslo (i.e. reached 26°C), Aberdeen and Inverness (i.e. reached 23°C) were similar during the fieldwork.

The Norwegian offices provided every occupant with a personal room and a high level of thermal control according to the Norwegian work regulations [40]. In contrast, the British practices provided thermal control for limited occupants seated around the perimeter of the open plan offices. The majority of the occupants seated away from the windows had no access to any means of thermal control. Award winning practice examples were selected for this comparison to ensure a good standard of indoor air quality and to limit the impact on user

comfort and satisfaction. Building performance was evaluated through environmental measurements, and in accordance with the standards and benchmarks (section 4). The ASHRAE standards were applied in this study as the most widely used measure of thermal comfort. Users' comfort and satisfaction were recorded through online survey questionnaires using a tablet computer in order to simplify the data collection, easier data storage, analysis and comparison, as well as to reduce the possibility of errors [53]. Simultaneous environmental measurement was applied. Participants' views of thermal control were also investigated through semi-structured interviews. Overall, 313 responses were received and all participants responded (response rate) to both questionnaire and interviews. Respondents were approached at least after an hour of their arrival to the building in order to eliminate the impact of adjustment to the thermal environment. The thermal environment as measured during the study period is presented in Table 1.

Table 1: Information regarding the researched floor in each building

Information regarding the floor of the building, which is included in the research						
Buildings	Floor area m ²	Number of workstations in each floor	Size of each workstation m ²	Workstations considered in this study	Male	Female
Building A	2000	100	10	95	53	42
Building B	840	24	14	77	41	36
Building C	1000	125	5	72	34	38
Building D	1680	525	3.5	69	37	32

Clothing convention and representative activities were observed. Generally summer clothing was worn (Clo 0.5) and sedentary activities took place in the buildings and this information was included in the PMV analysis, presented in section 4.4. The questionnaire included questions related to the ASHRAE Standard. Two key questions in the questionnaire were based on the ASHRAE seven-point scale [54], presented in Table 2.

Table 2: Extract from the questionnaire in regard to the thermal environment based on the ASHRAE seven-point scale [54]

Currently at my desk, regarding the thermal environment I feel:							
Very comfortable	Comfortable	Slightly comfortable	Neutral	Slightly uncomfortable	Uncomfortable	Very uncomfortable	No strong opinion
+3	+2	+1	0	-1	-2	-3	
Currently at my desk, the overall environment makes me feel:							
Very satisfied	Satisfied	Slightly satisfied	Neutral	Slightly dissatisfied	Dissatisfied	Very dissatisfied	No strong opinion
+3	+2	+1	0	-1	-2	-3	

The building performance was evaluated using environmental measurements and in accordance with the ASHRAE standard, as presented in section 4. Environmental measurements were applied to measure the particular thermal environment at the surveyed workstations and to evaluate the overall building performance: instant and constant measurements, respectively. The instant measurement was applied on the desk level at the surveyed workstations. For the constant measurement, particular measuring points were selected around the building on the floor, desk and ceiling levels, as demonstrated in Figure 1.

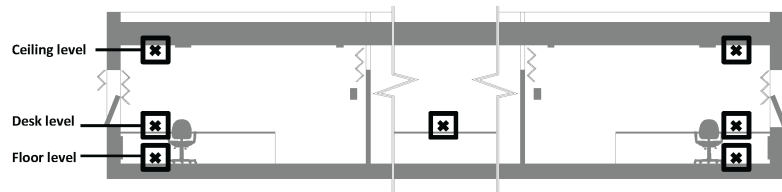


Figure 1: Sample of measuring points in Building B

Humidity, temperature and air monitoring equipment were used to measure the thermal environment, as presented in Table 3. Mean radiant temperature was calculated using the ASHRAE Thermal Comfort Tool 2 [55] and surface measurements using the constant measuring method. Statistical regression analysis was applied in this study, which is the main analysis method in the field studies of thermal comfort [56].

Table 3: Equipment for environmental measurements

Measurement	Time	Equipment details	Resolution	Accuracy	Range
Dry bulb temperature	Instant: at workstations	PCE-GA 70 air quality meter	0.1°C	±0.5°C	5 to 50°C
Relative humidity	Instant: at workstations	PCE-GA 70 air quality meter	0.1°C	±3 RH	10 to 90% RH
Carbon dioxide level	Instant: at workstations	PCE-GA 70 air quality meter	1 ppm	±50 ppm	6000 ppm
Dry bulb temperature	Constant: set in particular locations	Tiny Tag Plus 2 TGP-4500	0.01°C	0.01°C	-25 to +85°C
Relative humidity	Constant: set in particular locations	Tiny Tag Plus 2 TGP-4500	0.3% RH	±3% RH	0 to 100% RH

4. Building Performance

The study aimed to investigate the relationship between thermal control and user comfort and satisfaction. Therefore, an analysis of the building performance was undertaken to demonstrate that the thermal environment of the case study buildings were broadly compatible. The intention was therefore to help identify those issues related to environmental control and their impact on user satisfaction and comfort. The building performance of all four case study buildings were analysed in terms of the ventilation system, carbon dioxide level, energy and

thermal performance. Generally, sedentary activities took place in the buildings. The Norwegian offices (Buildings A and B) provided much larger workstations for each occupant compared to the British workplaces (Buildings C and D), as a personal room was provided for each occupant, as presented in Table 1 and Figure 2.

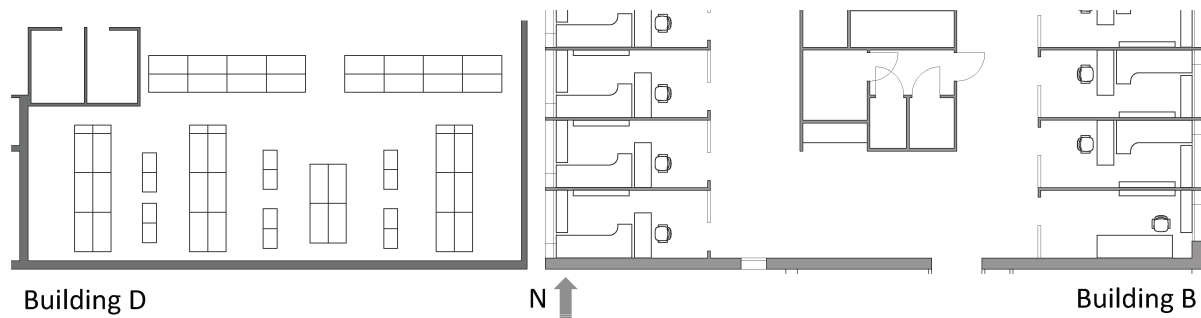


Figure 2: Sample plans of buildings B and D

4.1. Ventilation System

In the cellular plan offices, air conditioning was working and each occupant was provided with access to an openable window, blinds, door and the ability to adjust the cooling or heating. In the open plan offices, the centrally controlled mechanical system was operating, while only limited occupants seated around the perimeter of the building had access to openable windows and blinds, as presented in Figure 3. The mechanical systems operated from two hours in advance of the occupants' arrival until two hours after their departure and they were switched off over the weekends. The regular working hours in the Norwegian practices were eight to four and in the British offices nine to five. All four buildings receive direct solar gain during the day and occupants control it through blinds.

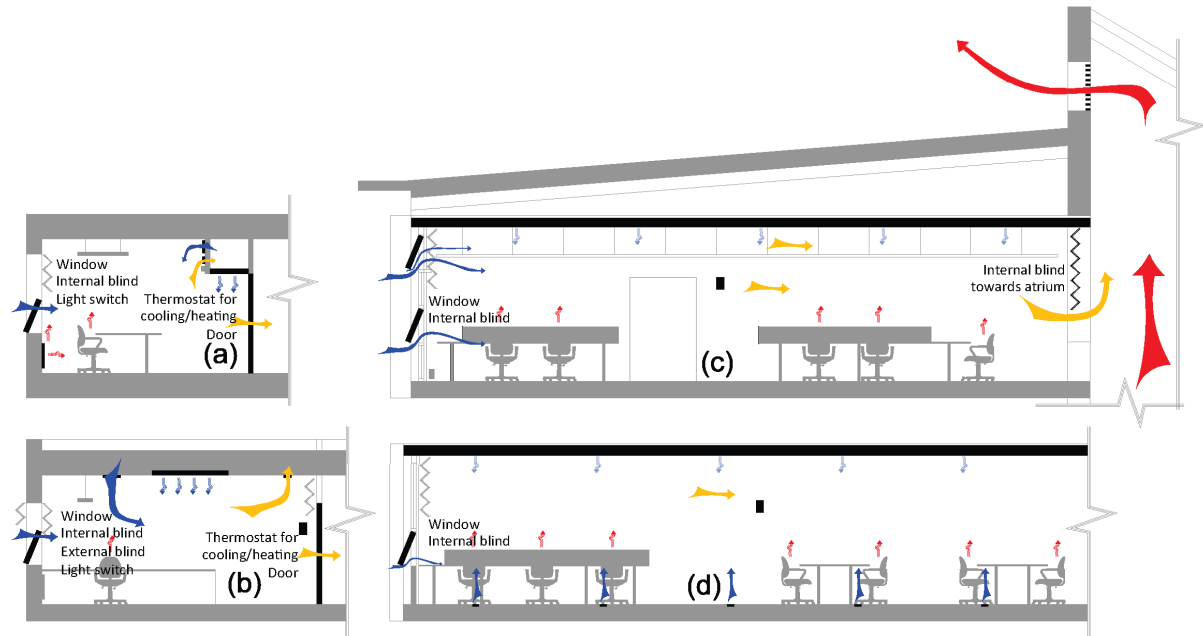


Figure 3: Sections of environmental control and summer day ventilation systems: (a), (b): Norwegian cellular plan offices and (c), (d): British open plan offices

Figure 3 also illustrates the summer day ventilation in the four buildings. In Building A, an openable window, mechanical ventilation, radiant cooling, and a radiator were in operation. Mechanical ventilation was centrally controlled and could not be adjusted by the occupant. In order to allow the occupant to change the room temperature, a thermostat and a temperature sensor were available for the occupant to adjust the temperature in the room. The thermostat was installed above the door of the office and it either switched on the radiator or the radiant cooling system in accordance with the current room temperature and the user's demand. This is the main cause for the high energy consumption in this building, as explained in section 4.3. In Building B, an openable window, mechanical ventilation and radiant cooling were in operation, which were controlled by the occupant through a temperature sensor and a controller unit installed next to the door of the office. Only air conditioning was centrally controlled and occupants had no control over it. Temperature sensors and centrally controlled thermal systems in the four buildings are illustrated in Figure 4.

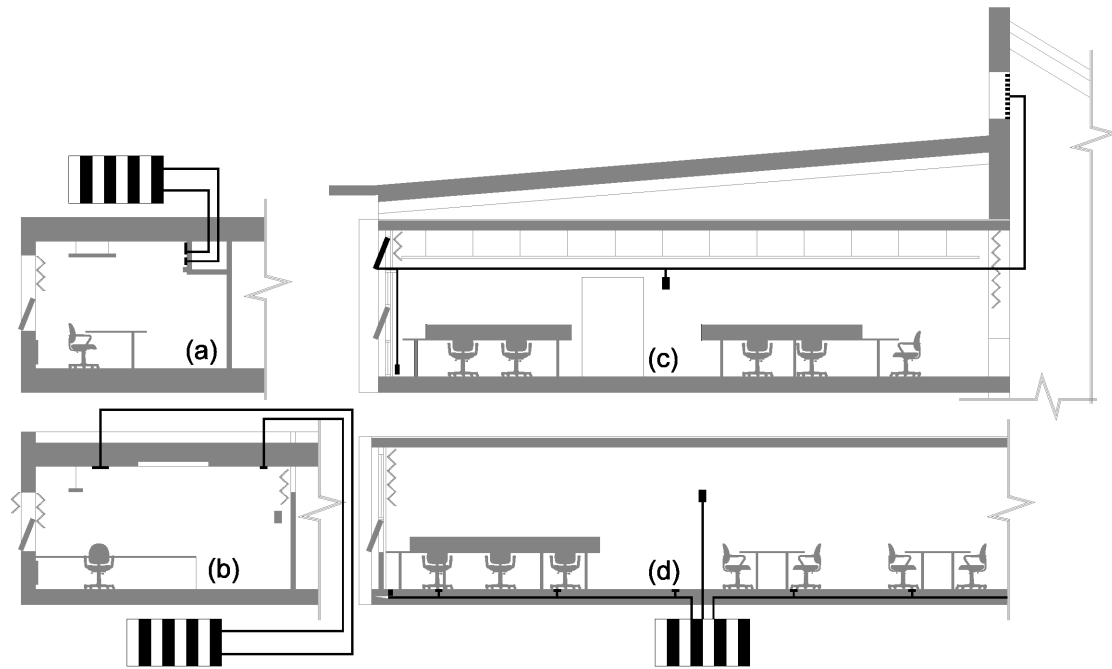


Figure 4: Sections, centrally controlled ventilation systems in (a) Building A, (b) B, (c) C, and (d) Building D

Building C was mainly a naturally ventilated building with automated top windows and vents to ensure a good indoor air quality and users did not have control over this part. Temperature and carbon dioxide sensors were installed on the two ends of the office to regulate the mechanical ventilation. The bottom windows were manually controlled by occupants. In Building D, openable windows and displacement ventilation were in operation. The former was controlled by occupants, while the latter was centrally controlled based on the information received via temperature sensors. This information is presented in Table 4. Ventilation rate was 4 air change rate per hour and air velocity was detected less than 0.1 m/s in all buildings, which was within the acceptable range.

Table 4: Heating, cooling and ventilation systems in the four buildings

Building	Location	Natural ventilation	Mechanical ventilation	Heating Installation	Heating working in summer?	Cooling installation
A	Norway	Openable windows	Mechanical ventilation-ceiling 4 air change rate per hour	Radiator	Yes	Radiant cooling
B	Norway	Openable windows	Mechanical ventilation-ceiling 4 air change rate per hour	Radiator	No	Radiant cooling
C	UK	Openable windows	Perimeter ventilation-automated top windows	Radiator	No	No
D	UK	Openable windows	Mechanical ventilation- underfloor – 4 air change rate per hour	Radiator	No	No

4.2. Carbon Dioxide Level

The carbon dioxide level of the four buildings was compared against the ASHRAE Standard [57]. It showed an acceptable indoor air quality and the carbon dioxide level of the majority of the workstations was below 600 ppm, as presented in Figure 5. The carbon dioxide level is lower in buildings B and C compared to the other two buildings, particularly building D, which is a deeper open plan office and the concentration of the carbon dioxide exceeded 800 ppm. Overall, the carbon dioxide level in all four buildings was within the acceptable range.

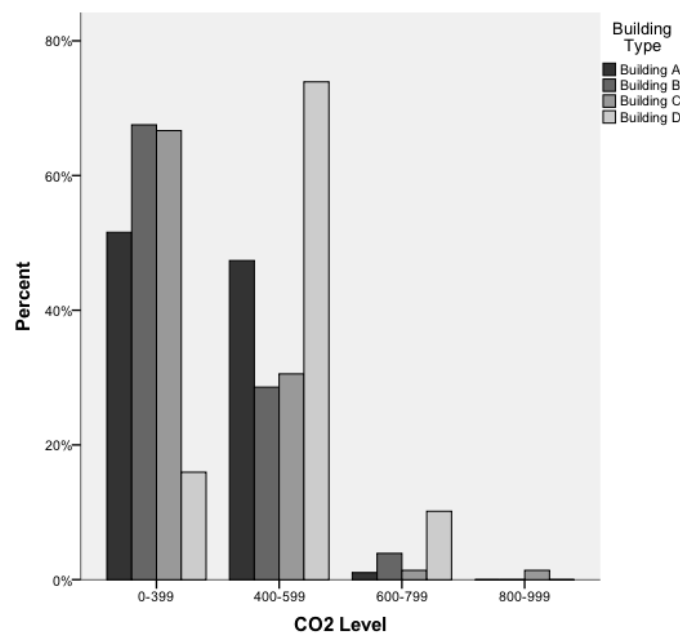


Figure 5: Carbon dioxide level: comparing the four case study buildings

The SPSS regression analysis showed no significant relationship between carbon dioxide level and comfort (P value = $0.433 > 0.05$) as well as satisfaction (P value = $0.120 > 0.05$).

4.3. Energy Consumption

The energy bills, which were provided by the management of the buildings, were analysed. The energy consumption analysis showed that except for one of the Norwegian cellular plan offices, all the other buildings are within the acceptable range of the CIBSE benchmark [58], as presented in Figure 6. Building A in particular had a much higher energy consumption that exceeds the limit (1550 Kwh/m^2 per year). This was mainly due to the application of contradictory thermal systems to provide occupants with thermal control and comfort, as

explained in section 4.1. Building C was the most energy efficient case study, due to the application of natural ventilation. Overall, the British open plan offices are much more energy efficient (150 and 160 Kwh/m² per year) compared to the Norwegian cellular plan offices (1550 and 550 Kwh/m² per year). Although the major part of the energy was consumed during the cold season, there was still a clear gap in the energy consumption of the Norwegian and British practices in summer. This suggests that providing individual thermal control comes at a price.

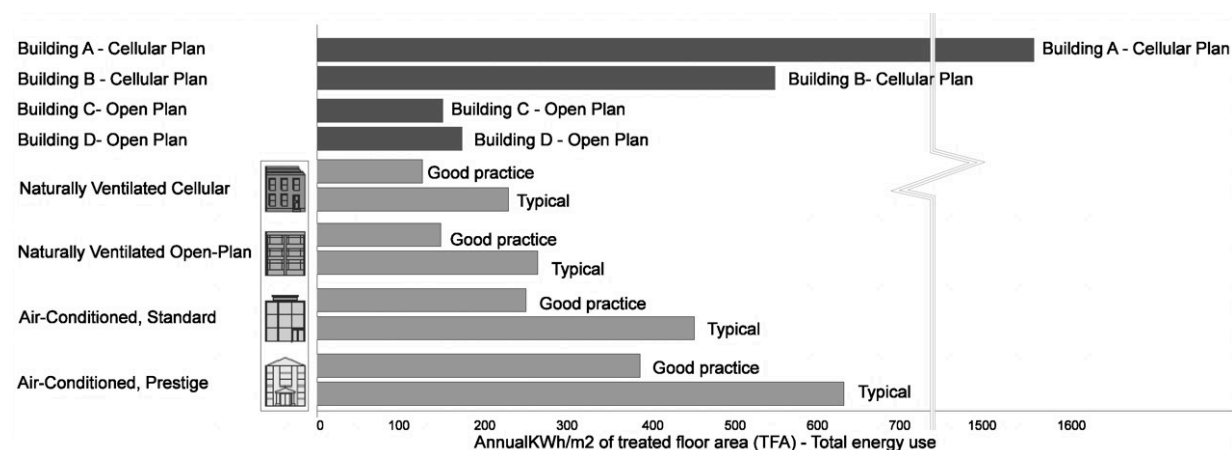


Figure 6: Energy consumption KWh/m² per year: comparing the buildings against the benchmark [58]

4.4. Thermal Comfort Predictions

The indoor climatic conditions in the case study buildings were steady. The Predicted Mean Vote (PMV) analysis was applied to examine the thermal performance of the four buildings using the ASHRAE Thermal Comfort Tool [55], which was based on the ASHRAE Standard 55-2010 [54]. Several thermal factors were considered in this analysis, including the dry bulb temperature, relative humidity, mean radiant temperature, air velocity, clothing, activity, location of the person in the room and from the walls and windows. The analysis indicated that the thermal environment of over 90% of the workstations agree with the comfort zone defined by ASHRAE Standard 55-2013 [60]. The occupants of the four buildings are expected to feel neutral or slightly cool, as presented in Figure 7.

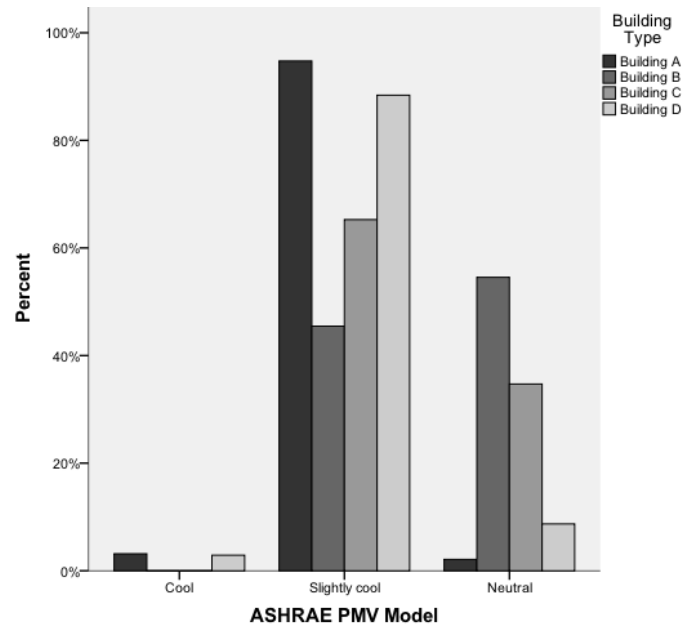


Figure 7: The PMV analysis

Figure 8 shows the thermal performance of the buildings against the ASHRAE Standard 55-2013 [60], which is in line with results of Figure 7. The thermal performance of all workstations was similar and within the acceptable range although many of them fell into the winter comfort zone (1 clo), particularly in buildings A and D. The management of the four buildings set the thermal environment according to the acceptable range. However, mainly dry bulb temperature was considered in their measurements. In contrast, in the analysis of this section operative temperature was considered (a combination of the Mean Radiant Temperature and the dry bulb temperature). The MRT was lower than the dry bulb temperature, therefore the operative temperature was closer to the lower boundary of comfort zone.

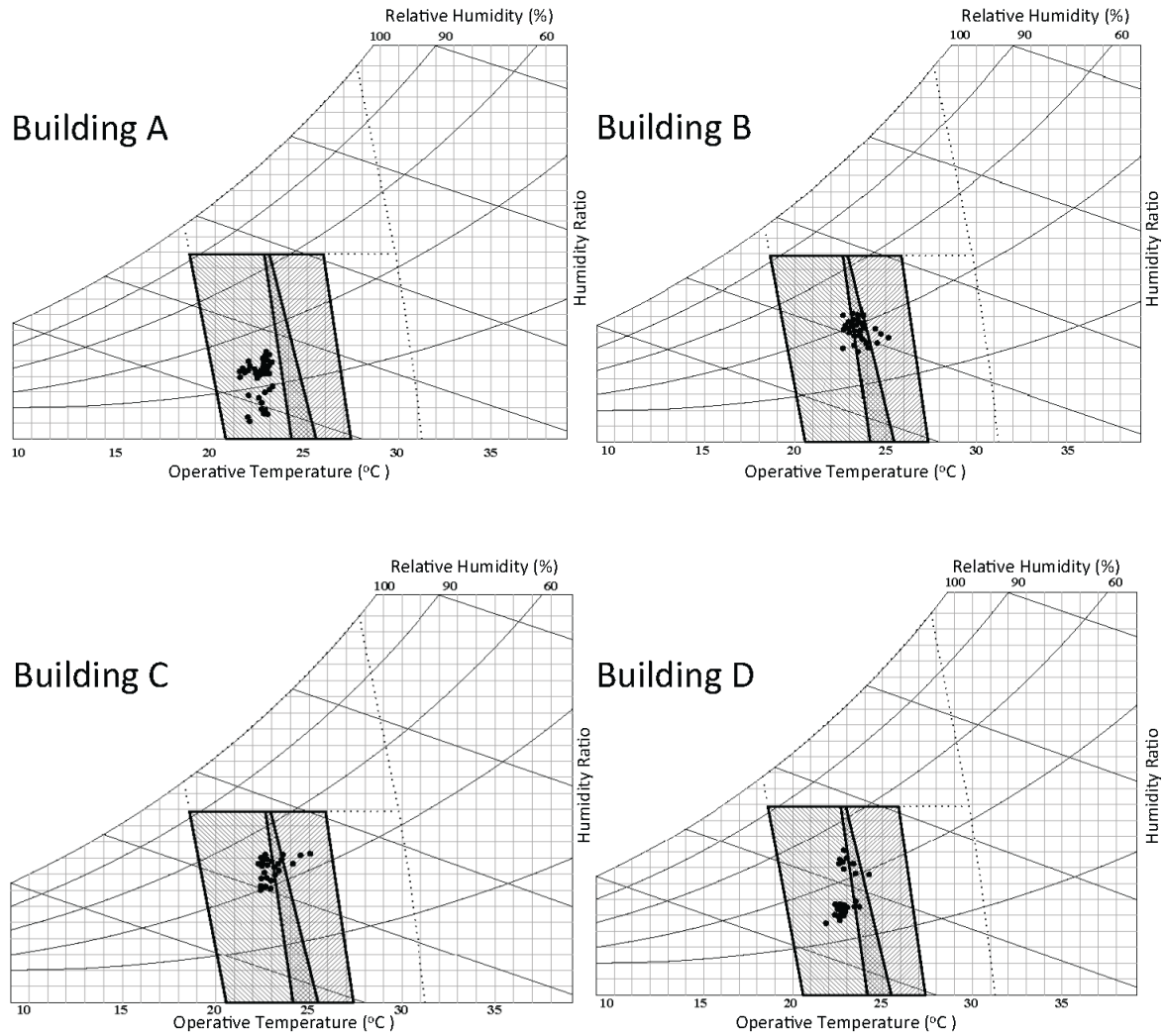


Figure 8: Thermal performance according to the ASHRAE Standard 55-2013 [60]

All four buildings provided high standards of indoor thermal environment and they were expected to provide comfortable thermal environments. Therefore, the comfort and satisfaction levels of the participants were less likely to be affected by a poor indoor air quality; this was confirmed in the follow up interviews. The regression analysis also confirmed this as well, as there was no significant relationship between the PMV and users' comfort ($P \text{ value} = 0.569 > 0.05$) and satisfaction ($P \text{ value} = 0.694 > 0.05$), as presented in Table 5.

Overall, the regression analysis showed no significant relationship between user comfort and satisfaction and environmental variables, including carbon dioxide, light, noise and thermal variable based on the PMV model, as presented in Table 5.

Table 5: Regression analysis of users' view and environmental variables

P values based on the SPSS linear regression analysis (P values > 0.05)				
	Carbon dioxide	Light	Noise	PMV
Comfort	0.433	0.250	0.946	0.569
Satisfaction	0.120	0.740	0.162	0.694

5. Individual Thermal Control

The comfort and satisfaction of the respondents between the Norwegian and British practices were compared using quantitative analysis of the survey questionnaires. This study was looking for high quality environments that provided users with unconditional satisfaction and comfort. Therefore from the ASHRAE seven-point scale, only two responses ('satisfied' and 'very satisfied') that represented a satisfaction status with confidence were considered as a 'satisfied' response. The same instruction was applied to evaluate comfort: only 'comfortable' and 'very comfortable' responses were considered as 'comfortable'.

5.1. Satisfaction

The relationship between satisfaction and the type of plan (cellular and open plan layouts) was investigated using the SPSS linear regression analysis on the survey questionnaires, as presented in Table 6. The ASHRAE scale [54] was used in the analysis, as presented in Table 2. Overall, the mean of satisfaction on this scale for all four buildings was 1.03: close to 'slightly satisfied'. The results indicated a significant relationship between satisfaction and the type of plan (P value = $0.000 < 0.05$). In addition, the regression analysis showed a significant relationship between satisfaction and the availability of thermal control (P value = $0.000 < 0.05$). Availability of thermal control was divided into five groups: no control; window or blind; both window and blind; window, blind, door and thermostat; window, internal and external blinds, door and thermostat. Building B provided the highest level of thermal control, due to an additional blind. The first three categories were in regard to the open plan offices and occupants seated in the middle of the open plan had no control over the thermal environment. Satisfaction was compared between the four buildings, as presented in Figure 9. The two darker bars representing the Norwegian buildings were similar and the number of 'satisfied' respondents was high. The satisfaction in the two British practices was also close and many respondents reported feeling 'slightly dissatisfied' and 'neutral'. The number of 'slightly dissatisfied' respondents is higher in building C compared to building D. Overall, the analysis indicated higher satisfaction levels in the two Norwegian cellular plan offices compared to the two British open plan offices.

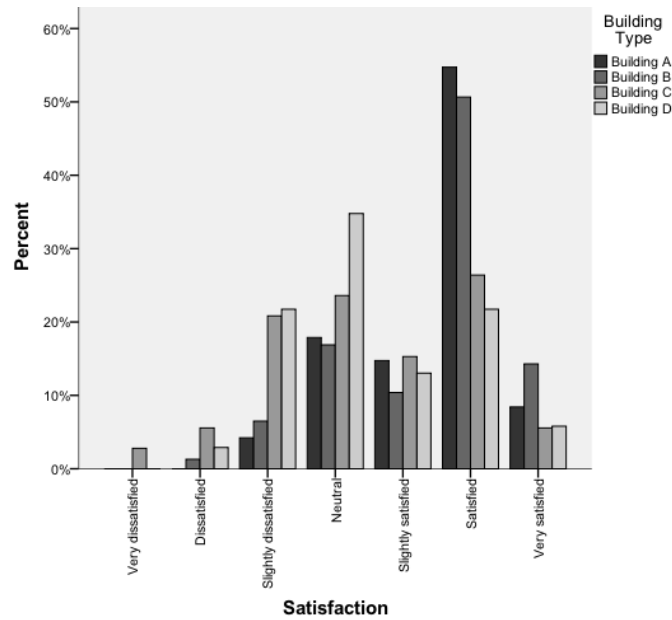


Figure 9: Satisfaction level in the four case study buildings

Based on the information presented in Figure 9, satisfied occupants ('satisfied' and 'very satisfied' responses) were calculated and presented in Table 6. The satisfaction level of the respondents of the cellular plan offices was at least 30% higher than that of the respondents of the open plan layouts.

Table 6: Satisfied respondents in the four buildings

Buildings	Percentage of satisfied respondents
Building A	63.10%
Building B	64.90%
Building C	32.00%
Building D	27.50%

5.2. Comfort

The relationship between user comfort and the type of plan was investigated using the SPSS linear regression analysis on the survey questionnaires, as presented in Table 7, and the ASHRAE scale [54], as presented in Table 2, was used in the analysis. Overall, the mean of satisfaction on this scale for all four buildings was 1.48, which is between 'slightly comfortable' and 'comfortable'. The results showed a significant relationship between the two variables ($P \text{ value} = 0.000 < 0.05$). In addition, the regression analysis showed a significant relationship between comfort and the availability of thermal control ($P \text{ value} = 0.000 < 0.05$), the categories are

explained in section 5.1. The comfort level was compared between the four buildings, as presented in Figure 10. It showed higher comfort levels in the two cellular plan offices compared to the two open plan offices.

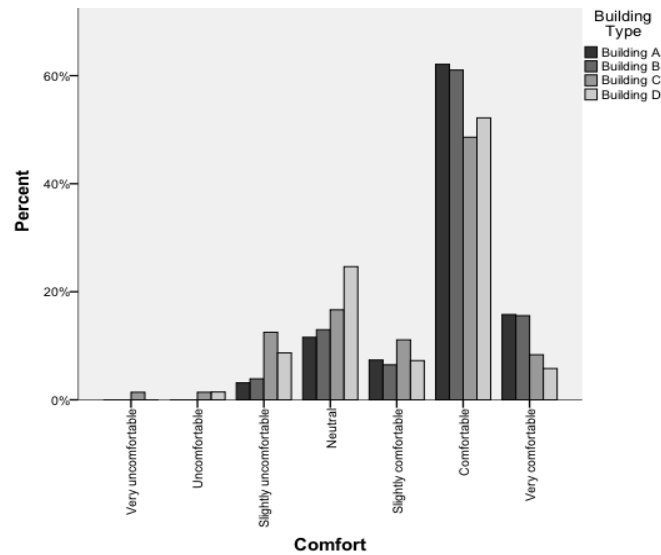


Figure 10: Comfort level in the four case study buildings

Based on the information presented in Figure 10, comfortable occupants ('comfortable' and 'very comfortable' responses) were calculated and presented in Table 7. The comfort level of the respondents for the Norwegian practices was at least 18% higher than that for the British buildings.

Table 7: Comfortable respondents in the four buildings

Buildings	Percentage of comfortable respondents
Building A	77.90%
Building B	76.60%
Building C	56.90%
Building D	58.00%

5.3. Interviews

In order to validate the results of the questionnaire, semi structured interviews were carried out and the interest of the respondents in their current office layout as well as using thermal control was investigated. Over 90% of the respondents of the cellular plan offices were not interested in moving into an open plan layout, due to the lack of thermal control and privacy. Over 70% of them actively adjusted the window, blind, door, or thermostat. They emphasised individual differences in perceiving the thermal environment. They found the thermal settings

of their colleagues' offices uncomfortable and, hence, preferred not to share an office with them. Over 70% of the participants of the open plan offices preferred to stay in the open plan layout, due to socialising and they considered personal offices as isolated. However, they expressed their dissatisfaction regarding the lack of thermal control at their workstation and also highlighted individual differences in perceiving the thermal environment. They tried to passively adjust themselves to the thermal environment. Although they had different clothing layers at their workstations, as presented in Figure 11, they did not consider this sufficient, convenient or satisfactory: 'Well, I change layers, but there is nothing more I can do'. There was a limit in taking off clothing layers, warming up cold hands and little that could be done about the lack of fresh air in the middle of the open plan office. In an extreme case, one respondent kept a sleeping bag in a drawer to wear when working in the cold winter days, as presented in Figure 11. Some respondents preferred to work from home when they found the thermal environment uncomfortable.



Figure 11: Sorting clothing layers and a sleeping bag in the British open plan office

Over 90% of the respondents of the Norwegian cellular plan offices preferred to have individual control over the thermal environment. However, 80% of the respondents of the British open plan offices initially preferred a centrally operated thermal system. Their main reasons being the 'others', who they shared an office with, their individual differences and the difficulty in satisfying everyone through a uniform thermal environment. They preferred not to be in charge of the temperature control to avoid the responsibility for setting an optimum temperature to satisfy everyone. Some respondents explained their previous experiences when a thermostat was available in the open plan office and the unpleasant arguments amongst colleagues to set the temperature. They were concerned about 'colleagues, who preferred extreme conditions, getting hold of the thermostat'. They preferred a centrally operated thermal system to set the temperature so that none of their colleagues could

tamper with it. A follow up question was posed: 'In case there were no other colleagues to be concerned about, would you still prefer a centrally operated thermal system?' Most of them immediately expressed their desire to control the temperature. The respondents, who generally preferred a centrally operated thermal system, did not want to spend time or energy on setting the temperature but wanted to focus on their work instead. However, even these respondents wanted a degree of control either to set the temperature in the beginning or in case they were uncomfortable.

6. Discussion

The results indicated that the Norwegian cellular plan offices with high levels of individual thermal control had higher levels of user satisfaction and comfort compared to the British open plan offices with limited thermal control. This was in line with the previous work stating that higher thermal control is associated with higher user comfort and satisfaction [6,42-49]. The significance of this study was in comparing the two distinct approaches (Norwegian and British) in providing thermal control in the workplace. This was related to the architectural design of the building, history, regulations and the contexts of the two countries, which lead to different ways of providing thermal control for occupants. The quantitative analysis of satisfaction and comfort (based on the survey questionnaires) indicated a significant relationship between these two variables and the type of plan. The occupants of the two Norwegian cellular plan offices reported at least a 30% higher satisfaction level and 18% higher comfort level compared to the occupants of the two British open plan offices. The follow up interviews rolled out the impact of other variables on user comfort and satisfaction, as occupants explained that the difference in their views was mainly due to the availability of thermal control for every individual in the Norwegian offices. Access to individual thermal control was the occupants' main priority, and the lack thereof resulted in their dissatisfaction, particularly in the open plan offices, as when uncomfortable they had no option but to tolerate the thermal condition. Some occupants put on inconvenient clothing layers or preferred to work from home. In addition, limited users, who had access to openable windows in the open plan, expressed their concerns and complexity of opening the windows or adjusting the blinds, as their action influenced other occupants' comfort in the room. Furthermore, the interviews revealed that the majority of the Norwegian occupants did not want to move into an open plan layout because of individual differences in thermal requirements and perceiving the thermal environment and lack of availability of thermal control.

The impact of different variables on occupant comfort was examined, as the complexity of the context followed by various variables that influence user comfort is a limit in the field studies of thermal comfort [7], such limits include psychological issues and social habits that are recommended for further research. In this study, the follow up interviews and other measures were taken to validate the results of the surveys and to limit the influence of the other factors as much as possible. The analysis based on the thermal measurements showed a good quality of building performance indicating a good quality of indoor thermal environment in all four buildings based on standards [60], and, thereby suggesting limited impact on user comfort and satisfaction. The timing for the fieldwork was carefully selected to reduce the impact of different climatic conditions on the indoor thermal environment, as the outdoor air temperature in summer months in Oslo was close to that in Aberdeen and Inverness. The regression analysis indicated no significant relationship between users' comfort and satisfaction levels and environmental variables, including carbon dioxide level, light, noise and PMV. The follow up interviews indicated the main factor influencing user comfort and satisfaction was recognised as the availability of thermal control followed closely by the architectural design of the buildings. The latter directly influenced the decision making of applying control over the thermal environment according to individual differences in perceiving the thermal environment.

The history of workplace design highlighted users' demand as access to individual thermal control. This study showed a significant difference between a workplace context that was built entirely based on this demand and a context that overlooked it. In the British context, the design of offices was based on organisational goals rather than users' satisfaction and the vague regulations did not support workers' rights. Availability of thermal control for occupants was not mentioned in the work regulations, hence it was not considered in the design of the workplace. The main approach to provide thermal comfort in the open plan office was the provision of a uniform, standard thermal environment [25] and a centrally operated thermal system. The adaptive opportunity, such as openable windows and blinds, were provided as a secondary system for 'fine-tuning' in case of a system failure [50] and in case occupants were uncomfortable [6]. Overall, thermal comfort was offered to occupants through a centrally operated system and optional adaptive opportunity was provided in case of inconvenience. This option was provided only for occupants seated around the perimeter of the building and majority of the users seated further from the windows were not provided with any means of control. In this study, the interviews indicated that even the occupants who had access to openable windows and blinds did not use them as desired, due to respecting 'other' colleagues' preferences. Occupants preferred not to access a thermostat in

the open plan office to avoid the responsibility to set a uniform temperature to satisfy all and due to individual differences in perceiving the thermal environment. However, their initial preference was to be able to adjust the temperature in case no 'other' colleagues were influenced by their decision.

In contrast, the Norwegian context was user-oriented and the work legislations supported users' right to access individual thermal control [1,40]. These were reflected in the design of the workplace: cellular plan offices with high levels of individual control over the thermal environment. This was the main thermal system and occupants were expected to adjust their thermal environment according to their requirements. Centrally operated thermal systems were considered as a secondary or background system to ensure a good quality of indoor environment according to workplace legislation [40]. In the Norwegian context, rather than presenting comfort to the occupant, the means to provide a comfortable condition were provided for every occupant so that individuals find their own comfort by actively using thermal control according to their immediate thermal needs. Individual differences were respected in this context and the office layout and thermal control were designed accordingly. In this study, the occupants of the Norwegian cellular plan offices expressed their satisfaction with the availability of individual control over the thermal environment. They did not want to share an office because they preferred to adjust the thermal environment in their personal rooms according to their needs. They expressed high satisfaction levels in regard to access to openable windows and the thermostat.

The main difference between the Norwegian cellular plan and the British open plan offices was not just the separation of workstations by walls, but in the context of providing high levels of individual thermal control. For instance, the management of building D, which was the British open plan building, had personal offices. However, they had no control over the thermal environment in their office except a glass door. Their personal offices had no windows, blinds or means to control the temperature and light. In the interviews, the occupants of the British personal offices expressed their dissatisfaction with the lack of availability of thermal control in their offices. This confirmed other studies, as the quality of the workplace environment was significantly different in these two contexts [10]. In contrast to the British practices the Norwegian case studies provided high levels of thermal control and therefore high user satisfaction. However, this came at a price: the two Norwegian practices were much less energy efficient compared to the two British practices. Inefficiency in energy and the use of space as well as being expensive and inflexible to respond to modern organisational changes [2,3] are the main causes of the move from cellular plan offices to open plan layouts in Scandinavia [4,5]. The case studies in this

work are either energy efficient or comfortable through providing thermal control for every individual. Although reducing the energy consumption is essential, user comfort is also important and providing a suitable environment for individuals is essential to maintain satisfaction and productivity accordingly [61]. Therefore, a balance between energy efficiency and providing comfort for individuals is required, as either extreme poses difficulties for the other. To achieve this, user orientated design must become integral to the building operation strategy.

7. Conclusion

This study investigated user comfort when different qualities of thermal control were provided in two distinct contexts. They followed two separate paths in designing the workplace: user-oriented and business-oriented with high and low levels of thermal control, respectively. Although previous research emphasised the impact of thermal control on user comfort and satisfaction [6,42-49], they were mainly applied in open plan settings, where thermal control was considered as a secondary option for fine-tuning. This work compared such settings with personal offices that based on Norwegian regulations provided high levels of thermal control for every individual. This is the main source of regulating the thermal environment so that each individual finds their own comfort in a way that it does not influence the settings and comfort of other occupants. Currently in practice, such settings are being replaced by open plan layouts with limited thermal control and management prefer centrally operated thermal systems rather than user control. This study highlighted the impact of the architectural design of the workplace and providing thermal control on occupants' comfort and satisfaction. Individual differences were highly respected in the Norwegian context and therefore reflected in the architectural design of the building, as rooms with an outside view, access to natural light and ventilation were provided for each occupant. Privacy and high levels of thermal control for every individual were provided. In contrast, in the British context, efficiency of use of space, teamwork and communication were highly valued, which were reflected in the architectural design of the workplace in the form of open plan layouts. As a consequence, limited thermal control was available only for occupants seated around the perimeter of the building and majority of the occupants seated away from the windows had no access to any means of thermal control. Comfort and satisfaction of occupants in the two Norwegian cellular plan offices were up to 30% higher than that in the two British open plan offices. Furthermore, this study found the impact of the architectural design of the building on the decision making of occupants in using the available thermal control. Occupants of the open plan office were cautious to open the windows and the influence on the other occupants in the open

plan setting, while the occupants of the personal offices enjoyed the autonomy in using the available thermal control as was they felt required knowing that it did not influence the comfort of other colleagues.

This study found that a balance between energy consumption and thermal comfort is dependant on the provision of individual control over the thermal environment to achieve user comfort and satisfaction. There is a disagreement in predicting the necessity of providing thermal control in the future, as Leaman and Bordass (2005) recognised it as an essential asset [9], while Harris (2006) claimed it as unnecessary, due to flexible ways of working rather than assigned workstations [8]. This study highlighted the importance of providing individual control over the thermal environment in the workplace as well as the architectural design of the workplace based on individual requirements. Overall, rather than presenting comfort to the occupants, buildings should provide a degree of flexibility in a sustainable way to allow users to adjust their thermal environment according to their individual requirements to find their own comfort.

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References

- [1] Van Meel, J. 2000. *The European Office: Office Design and National Context*, Rotterdam, 010 Publishers.
- [2] Van Meel, J. & De Jonge, H. 2006. *Office Cultures: International Differences in Workplace Design*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, Elsevier.
- [3] Myerson, J. 2008. *Power of the Network: Transitions in Working Life from Taylorist Time and Motion to Networked Space*. In: Glynne, J. & Iackney, F., eds. *Networks of Design: Proceedings of the 2008 Annual International Conference of the Design History Society (UK)*, 2008 University College Falmouth. Universal Publishers.
- [4] Axéll, C. & Warnander, A. 2005. *How to Create Optimal Office Solutions*. MSc, KTH University.
- [5] Gadsjö, A. 2006. Hur påverkas hyresgästanpassningar framtida hyresintäkter? (How Does Improvement in Tenant Influence The Future of Rental Income?). KTH.
- [6] Bordass, B., Bromley, K. & Leaman, A. 1993. *User and Occupant Controls in Office Buildings*. Building Use Studies.
- [7] Roaf, S., Horsley, A. & Gupa, R. 2004. *Closing the loop; Benchmarks for sustainable buildings*, London, RIBA Enterprises Ltd.
- [8] Harris, R. 2006. *Real Estate and the Future*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, Elsevier.
- [9] Leaman, A. & Bordass, B. 2005. *Productivity in buildings: The 'killer' variables*. Building Research and Information, 27, 4-19.

- [10] Duffy, F. 1992. *The Changing Workplace*, London, Phaidon Press Limited.
- [11] Myerson, J. 2008. *Power of the Network: Transitions in Working Life from Taylorist Time and Motion to Networked Space*. In: Glynne, J. & Iackney, F., eds. *Networks of Design: Proceedings of the 2008 Annual International Conference of the Design History Society (UK)*, 2008 University College Falmouth. Universal Publishers.
- [12] Taylor, F. W. 1915. *Expert in Efficiency, Dies*. New York Times.
- [13] Klein, J. G. 1982. *The Office Book*, London, Qurto Marketing Ltd.
- [14] Duffy, F., Laing, A. & Crisp, V. 1993. *The Responsible Workplace*, London, DEGW and the Building Research Establishment.
- [15] Forty, A. 1986. *Objects of Desire: Design and Society: 1750*, Thames & Hudson.
- [16] Hookway, B. 2009. *Rules of Engagement: Arhchitecture Theory and the Social Sciences in Frank Duffy's 1974 Thesis on Office Planning*, Princeton University.
- [17] Laing, A. 2006. *New Patterns of Work: The Design of the Office*. In: Worthington, J. (ed.) *Reinventing the Workplace*. London: Architectural Press, DEGW.
- [18] Marmot, A. & Eley, J. 2000. *Office Space Planning; Design for Tomorrow's Workplace*, New York, London, Sydney, McGraw-Hill.
- [19] Allen, T. J. & Gertberger, P. G. 1971. *Working Paper*: Alfred P. Sloan school of Management. Massachusetts Institute of Technology.
- [20] Gottschalk, O. 1994. *Verwaltungsbauten: flexibel, kommunikativ, nutzerorientiert*, Berlin, Bauverlag GmbH.
- [21] Klein, N. 1998. *No Logo*, London, Flamingo.
- [22] Harrison, A., Wheeler, P. & Whitehead, C. 2004. *The Distributed Workplace*, London, Spon Press.
- [23] Kubzansky, P. E. 1982. *Optimizing Open Office Environments: A symposium*. 13th International Conference of the Environmental Design Research Association, 1982 College Park, Maryland.
- [24] Pile, J. 1976. *Interiors 3rd Book of Offices*, New York, Watson Guptill Publications.
- [25] Nicol, F., Humphreys, M. A. & Roaf, S. 2012. *Adaptive Thermal Comfort: Principles and Practice*, Routledge.
- [26] Brookes, M. J. & Kaplan, A. 1972. *The Office Environment: Space Planning and Affective Behavior* Human Factors, 14, 373-391.
- [27] Hedge, A. 1982. *The Open Plan Office: A Systematic Investigation of Employee Reactions to Their Work Environment*. Environment and Behaviour, 14, 519-542.
- [28] Ives, R. S. & Ferdinands, R. 1974. *Working in a Landscaped Office*. Personal Practice Bulletin, 30, 126-141.
- [29] Mercer, A. 1979. *Office Environments and Clerical Behavior*. Environment and Planning, 6, 29-39.
- [30] Nemecek, J. & Grandjean, E. 1973. *Results of an Ergonomic Investigation of Large-Space Offices*. Human Factors, 15, 111-124.
- [31] Oldham, G. R. & Brass, D. 1979. *Employee Reactions to an Open Plan Office: A Naturally Occuring Quasi-Experiment*. Administrative Science Quarterly 24, 267-284.
- [32] Sundstorm, E., Burt, R. E. & Kamp, D. 1980. *Privacy at Work: Architectural Correlates of Job Satisfaction and Job Performance*. Academy of Management Journal, 23, 101-117.
- [33] Marans, R. W. & Yan, X. 1989. *Lighting Quality and Environmental Satisfaction in Open and Enclosed Offices*. Journal of Architectural and Planning Research, 6, 118-131.
- [34] Brennan, A., Chugh, J., S. & Kline, T. 2002. *Traditional versus Open Office Design: A Longitudinal Field Study*. Environment and Behaviour, 34, 279.
- [35] Hundert, A. T. & Greenfield, N. *Physical Space and Organizational Behavior*. Proceedings of the 77th Annual Convention, APA, 1969. 601-602.
- [36] Becker, F. 1981. *Work Space: Creating Environments in Organizations*, New York, Praeger Publications.
- [37] Van Der Voordt, T., J. M. 2003. *Productivity and Employee Satisfaction in Flexibile Workplaces*. Journal of Corporate Real Estate, 6, 133-148.
- [38] Eaton, K. 1997. *Medical aspect*. In: Rostron, J. (ed.) *Sick Building Syndrome; Concepts, issues and practice*. London

- [39] Meir, I. A., Carb, Y., Jiao, D. & Cicelsky, A. 2009. *Post Occupancy Evaluation: An Inevitable Step Toward Sustainability*. Advances in Building Energy Research, Earthscans Journals. Santamouris: aber.
- [40] Arbeidstilsynet 2003. Control and Guidance on Working: Veiledning om klima og luftkvalitet på arbeidsplassen - fulltekst. In: Arbeidstilsynet (ed.). Norway.
- [41] HSE. 1992. *Workplace Health, Safety and Welfare: Regulation 1992*, Approved Code of Practice. In: Executive, H. A. S. (ed.). *Health and Safety Executive*.
- [42] Melikov, A. 2004. *Personilised Ventilation*. Indoor Air, 14, 157-167.
- [43] Arens, E., Humphreys, M. A., De Dear, R. & Zhang, H. 2010. *Are 'Class A' Temperatue Requirements Realistic or Desirable?* Building and Environment, 45, 4-10.
- [44] Leaman, A. 1996. *User satisfaction*. Building evaluation techniques. London: McGraw.
- [45] De Dear, R. & Brager, G. 2002. Thermal Comfort in Naturally Ventilated Buildigns: Revisions to ASHRAE Standard 55. Energy and Buildings, 34, 6: 549-561
- [46] Baker, N. & Standeven, M. 1995. *A Behavioural Approach to Thermal Comfort Assessment*. International Journal of Solar Energy, 19, 21-35.
- [47] Humphreys, M. A. 1996. Thermal Comfort Temperatures World-Wide: The Current Position. WREC 1996.
- [48] Wagner, A., Gossauer, E., Moosmann, C., Gropp, T. & Leonhart, R. 2007. Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings. Energy and Building, 39, 758-769.
- [49] Newsham, G., Brand, J., Donnelly, C., Veitch, J., Aries, M. & Charles, K. 2009. *Linking Indoor Environment Conditions to Job Satisfaction: A Field Study*. Building Research and Information, 39, 129-147.
- [50] Hawkes, D. 2002. *The Selective Environment; An approach to environmentally responsive architecture*, London, Spon Press.
- [51] Nicol, F. & Humphreys, M. A. 2005. *Maximum Temperature in Buildings to Avoid Heat Discomfort*. International Conference 'Passive and Low Energy Cooling for the Built Environment'. Santorini, Greece.
- [52] Tuohy, P., Rijal, H. B., Humphreys, M. A., Nicol, J. F., Samuel, A. & Clarke, J. *Comfort driven adaptive window opening behaviour and the influence of building design*. Building simulation, 2007.
- [53] Brager, G. S. & Baker, L. 2009. *Occupant Satisfaction in Mixed-Mode Buildings*. Building Research and Information, 37, 369-380.
- [54] ASHRAE 2009. *ASHRAE Handbook: Fundamentals*. SI Edition ed. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- [55] Huizenga, C. 2011. *ASHRAE Thermal Comfort Tool CD, Version 2*: Maintains Consistency with ANSI/ASHRAE Standard 55-2010. ASHRAE.
- [56] McCartney, K. J. & Nicol, F. 2002. *Developing an Adaptive Control Algorithm for Europe*. Energy and Buildings, 34, 623-635.
- [57] ASHRAE 2001. *ASHRAE Fundamental Handbook*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- [58] CIBSE 2003. *Energy Consumption Guide 19: Energy Use in Offices. Best Practice Programme*. The Chartered Institution of Building Services Engineers.
- [59] ASHRAE 2010. *ASHRAE Standard 55*. In: Cooper & W., K. (eds.) *Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- [60] ASHRAE 2013. *ANSI/ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- [61] Charkham, J., P. 1995. *Keeping Good Company: A Study of Corporate Governance in Five Countries*, Oxford, Oxford University Press.